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(Dated: 14th January 2004)

The Standard Model (SM) of particle physics contains about two dozen para-meters – such as masses of quarks and leptons – whose origins are still unknown and cannot be predicted within the Model, but whose values are constrained through their interactions. In particular, the masses of the top quark (M_t) and W boson (M_W) [1] constrain the mass of the hypothesized Higgs boson – the last remaining particle predicted by the Standard Model that has not yet been observed. A light Higgs particle is expected in several popular models, includ-ing supersymmetry. Indirect constraints on the mass of the Higgs particle are extremely sensitive to the top mass. A potential problem for the SM is that, based on the presently accepted mass of the top quark, the most likely value of the Higgs mass [2] lies in a range that has already been excluded by experiment [3]. Here we report a determination of the top quark mass of $M_t = 180.1 \pm 5.3$ GeV/c^2, using a new method of analysis performed by the DØ Collaboration at the Fermilab Tevatron proton-antiproton collider. Combined with our previ-ously published measurement of the top mass [4], this yields $M_t = 179.0 \pm 5.1$ GeV/c^2, i.e., one standard deviation higher than the previous world average. This value corresponds to an increase of the most likely value of the Higgs mass by more than 30%, from 96 GeV/c^2 [2], which is in the excluded region, to 123 GeV/c^2, a value more consistent with experiment. This shift in the most likely Higgs mass improves the self-consistency of the Standard Model, which has been questioned in a number of recent papers, e.g. [5].

The observation of the top (t) quark served as one of the major confirmations of the validity of the SM [6, 7]. Of its many parameters, the mass of the top quark, in particular, reflects some of the most crucial aspects of the Model. This is because, in principle, the top quark is point-like and should be massless; yet, through its interactions with the Higgs field that supposedly permeates our entire universe, the physical mass of the top quark appears to be about the mass of a gold nucleus, or of order 200 proton masses. Because it is so heavy, the top quark (along with the W boson) provides an unusually sensitive tool for investigating the Higgs field. M_W is known to a precision of 0.05%, while the uncertainty on M_t is at the 3% level [1]. Improvements in both measurements are required to restrict further the allowed range of mass for the Higgs. Precise knowledge of the Higgs mass is crucial for our understanding of the SM and any possible new physics beyond it. For example, in a large

class of supersymmetric models (theoretically preferred solutions to the deficiencies of the SM), the Higgs mass has to be less than $\approx 135\,\mathrm{GeV}/c^2$. If the Higgs turned out to be heavier than that, the existence of low-scale supersymmetry would be essentially ruled out.

The DØ experiment at the Fermilab Tevatron studied a sample of $t\bar{t}$ events produced in proton-antiproton ($p\bar{p}$) interactions [8]. The total energy of 1.8 TeV released in a head-on collision of a 900 GeV p and 900 GeV $\bar{p}$ is almost as large as the rest energy of ten gold nuclei. Each top (antitop) quark decays almost immediately into a bottom b ($\bar{b}$) quark and a W^+ (W^-) boson, and we have re-examined those events in which one of the W bosons decays into a charged lepton (electron or muon) and a neutrino, and the other W into a quark and an antiquark (see Figure 1). These events and their selection criteria are identical to those used to extract the mass of the top quark in our previous publication, and correspond to an integrated luminosity of 125 events/pb. (That is, given the production cross section of the $t\bar{t}$ in $p\bar{p}$ collisions at 1.8 TeV of 5.7 pb, as measured by DØ [9], these data correspond to approximately 700 produced $t\bar{t}$ pairs.) The previous DØ result in this channel is $M_t = 173.3 \pm 5.6$ (stat)± 5.5 (syst) GeV/c^2. Information pertaining to the detector and to the older analysis can be found in Refs. [10] and [8], respectively.

The new mass measurement method is similar to one suggested [11] for $t\bar{t}$ dilepton decay channels (where both W bosons decay leptonically), and used in previous mass analyses of dilepton events [4], and akin to an approach suggested for the measurement of the mass of the W boson at LEP [12]. The critical differences from the previous analyses in the lepton plus jets decay channel are: (i) assignment of a higher weight to events that are better measured or are more likely to correspond to $t\bar{t}$ signal, and (ii) better accounting for combinatorics due to several possible assignments of the final-state objects (lepton, jets, and missing transverse momentum, the latter being a signature for an undetected neutrino) to the top-quark decay products (e.g., due to the ambiguity in choosing the jets that correspond to the b and $\bar{b}$ quarks from the decays of the t and $\bar{t}$ quarks). We calculate, as a function of top mass, the differential probability that the measured variables in any event correspond to signal. The maximum in the product of these probabilities provides the best estimate of the mass of the top quark in the data sample. For details on the new method, see the section on Top Mass Extraction.

As in the previous analysis [8], γ+jet events were used to check the jet energy scale (JES) in the experiment relative to Monte Carlo (MC) simulation. This calibration had an

uncertainty of $\delta E = (0.025\ E + 0.5\ \text{GeV})$. Consequently, all jet energies in our sample were re-scaled by $\pm \delta E$, the analysis redone, and half of the difference in the two rescaled results for M_t ($\delta M_t = 3.3\ \text{GeV}/c^2$) was taken as the systematic error from the uncertainty in the JES. All other contributions to systematic uncertainty are far smaller [13].

The final result is $M_t = 180.1 \pm 3.6\ (\text{stat}) \pm 3.9\ (\text{syst})\ \text{GeV}/c^2$. The improvement in statistical uncertainty over our previous measurement is equivalent to collecting a factor of 2.4 as much data. The analysis is also less sensitive to the JES, which leads to a smaller systematic uncertainty. Combining the statistical and systematic uncertainties in quadrature, we obtain $M_t = 180.1 \pm 5.3\ \text{GeV}/c^2$, which has a precision comparable to all the previous measurements [1] combined.

The new measurement can be combined with that obtained for the dilepton sample also collected at DØ during Run I [4], to yield the new DØ average for the mass of the top quark:

$$M_t = 179.0 \pm 3.5\ (\text{stat}) \pm 3.8\ (\text{syst})\ \text{GeV}/c^2 \tag{1}$$

This result corresponds to the most accurate measurement of the top quark mass in any single experiment and shifts the value of the expected Higgs mass to $123\ \text{GeV}/c^2$ (see Figure 2), which is consistent with the experimentally excluded region and still can be accessed in the current run of the Tevatron and at future runs at the Large Hadron Collider.

Top Mass Extraction

The new method for extracting the mass of the top quark provides substantial improvement in both statistical and systematic uncertainties. This can be attributed primarily to the fact that: (i) each event now has its individual probability as a function of the mass parameter, and therefore well-measured events contribute more sharply to the extraction of the top mass than those poorly measured, and (ii) all jet and neutrino combinations (and not just the most likely one) are included, which guarantees that all events contribute to the measurement.

The probability density as a function of M_t can be written as a convolution of the calculable cross section and any effects from detector measurement resolution:

$$P(x, M_t) = \frac{1}{\sigma(M_t)} \int d^n \sigma(y, M_t) dq_1 dq_2 f(q_1) f(q_2) W(y, x) \tag{2}$$

where $W(y, x)$, our general transfer function, is the normalized probability for the measured set of variables x to arise from a set of nascent (partonic) variables y, $d^n \sigma(y, M_t)$ is the

partonic differential cross section, $f(q)$ are parton distribution functions that reflect the probability of finding any specific interacting quark (antiquark) with momentum q within the proton (antiproton), and $\sigma(M_t)$ is the total cross section for producing $t\bar{t}$. The integral in Eq. (2) sums over all possible parton states leading to what is observed in the detector.

The impact of biases from imperfections in the detector and event reconstruction algorithms is taken into account in two ways. Geometric acceptance, trigger efficiencies, event selection, etc., enter through a multiplicative function $A(x)$ that is independent of M_t, and that relates the probability $P_m(x, M_t)$ of measuring the observed variables x to their production probability $P(x, M_t)$: $P_m(x, M_t) = A(x)P(x, M_t)$. Effects from energy resolution, etc., are taken into account in the transfer function, $W(y, x)$ (see below).

Since the angular directions of all the objects in the event, as well as the electron momentum are measured with high precision, their measured values are used directly in the calculation of the probability that any event corresponds to $t\bar{t}$ or background production. To account for a measurement uncertainty due to imperfect muon detector resolution, the known momentum smearing function [14] is used. The integrations over essentially fifteen well-measured variables (three components of charged-lepton momentum, eight jet angles, and four equations of energy-momentum conservation), leave five integrals that must be performed to obtain the probability that any event represents $t\bar{t}$ (or background) production for some specified value of top mass M_t.

The probability for a $t\bar{t}$ interpretation can be written as:

$$P_{t\bar{t}} = \frac{1}{12\sigma_{t\bar{t}}} \int \mathrm{d}\rho_1 \mathrm{d}m_1^2 \mathrm{d}M_1^2 \mathrm{d}m_2^2 \mathrm{d}M_2^2 \times \sum_{\mathrm{perm.},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \Phi_6 W_{\mathrm{jets}}(E_{\mathrm{part}}, E_{\mathrm{jet}}),$$

For $|\mathcal{M}_{t\bar{t}}|^2$, we use the leading-order matrix element [16], $f(q_1)$ and $f(q_2)$ are the CTEQ4M parton distribution functions for the incident quarks [17], Φ_6 is the phase-space factor for the 6-object final state, and the sum is over all 12 permutations of the jets and all possible neutrino solutions. $W_{\mathrm{jets}}(E_{\mathrm{part}}, E_{\mathrm{jet}})$ corresponds to a function that maps parton-level energies E_{part} to energies measured in the detector E_{jet}, and is based on MC studies. A similar expression, with a matrix element that is independent of M_t, is used to describe the background processes.

Studies of samples of HERWIG [15] MC events used in the former analysis indicate that the new method is capable of providing almost a factor of two reduction in the statistical uncertainty on the extracted M_t. These studies also reveal that there is a systematic shift in

the extracted M_t that depends on the amount of background in the data. To minimize this effect, a selection is introduced based on the probability that an event represents background from W+jets. The selected value of $P_{\text{bkg}} < 10^{-11}$ was based on MC studies carried out before applying the method to data, and, for a top mass of 175 GeV/c^2, retains 71% of the signal and 30% of the background. A total of 22 data events pass this cut.

To illustrate the separation between the top signal and background, a discriminant $D = P_{t\bar{t}}/(P_{t\bar{t}} + P_{\text{bkg}})$ is defined to quantify the likelihood for an event to correspond to signal at the most likely value of M_t [5]. Figure 3 shows a comparison of the discriminant calculated for data and for MC events. Since the discriminant depends on the top mass, it was not used to reject background and is shown simply to illustrate the level of discrimination of signal from background.

The final likelihood as a function of M_t is written as:

$$\ln L(M_t) = \sum_{i=1}^{N} \ln[c_1 P_{t\bar{t}}(x_i; M_t) + c_2 P_{\text{bkg}}(x_i)] - N \int A(x)\, [c_1 P_{t\bar{t}}(x; M_t) + c_2 P_{\text{bkg}}(x)]\, \mathrm{d}x,$$

These integrals are calculated using MC methods. The best value of M_t represents the most likely mass of top in the final N-event sample, and the parameters c_i reflect amount of signal and background. M_t and c_i are obtained by minimizing $-\ln L(M_t)$. MC studies show that there is a shift down of 0.5 GeV/c^2 in the extracted mass, and this correction is applied to the result. Reasonable changes in the cutoff on P_{bkg} do not have significant impact on M_t.

Figure 4 shows the value of $L(M_t)/L_{\text{max}}$ as a function of M_t for the 22 events that pass all selection criteria, after correction for the above top mass bias. To obtain L_{max}, the likelihood is maximized with respect to the parameters c_i at each mass point. The Gaussian fit in the figure yields $M_t = 180.1$ GeV/c^2 with a statistical uncertainty of $\delta M_t = 3.6$ GeV/c^2. Combined with our earlier result [4], and accounting for systematic uncertainty, the new DØ combined Run I measurement yields the top mass of 179.0 ± 5.1 GeV/c^2.

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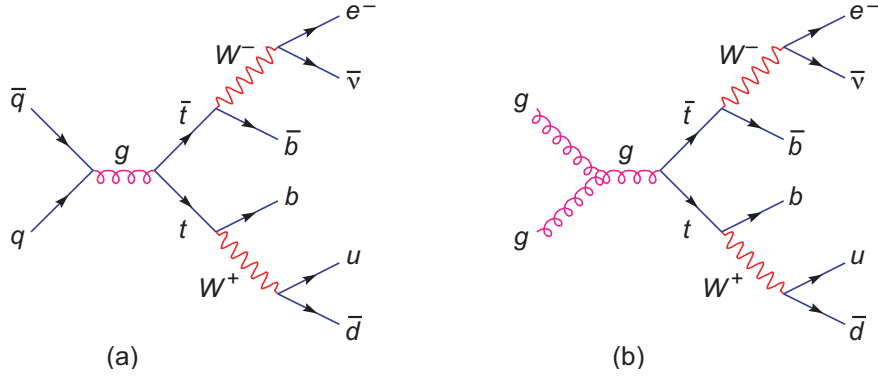
Figure 1: Feynman diagrams for $t\bar{t}$ production in $p\bar{p}$ collisions, with subsequent decays into an electron, neutrino, and quark jets. Diagram (a) (quark-antiquark production) is dominant, but diagram (b) (gluon fusion) contributes an additional 10% to the cross section. This particular final state ($e\bar{\nu}u\bar{d}$) is one of several possible final states used in the analysis.
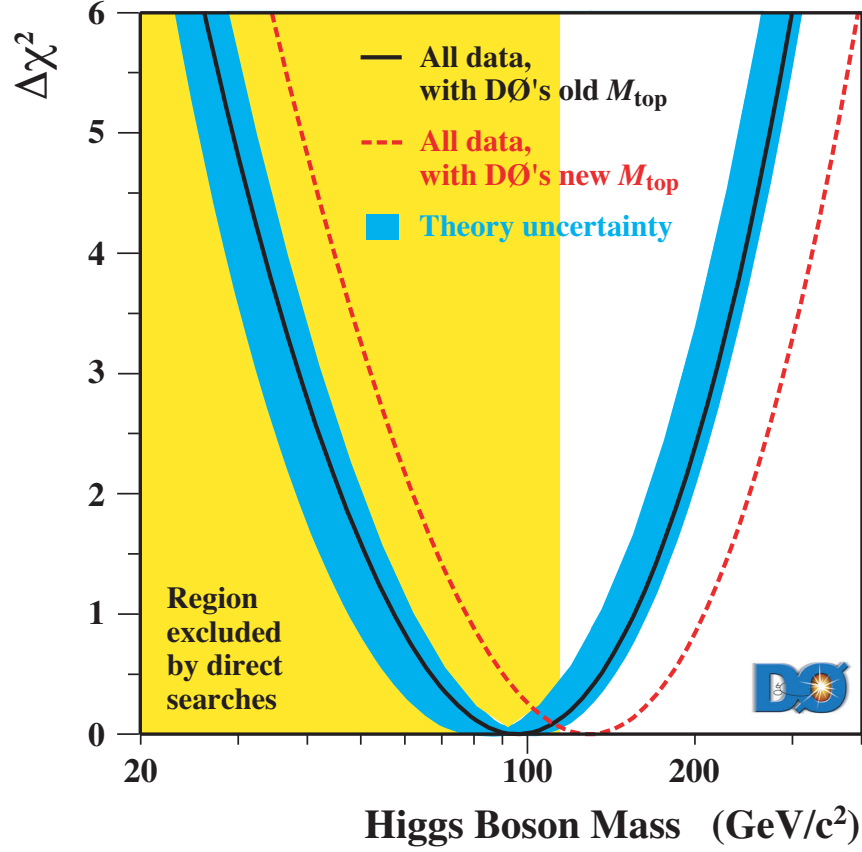
Figure 2: χ^2 for a global fit to electroweak data using the procedure of Ref. [2], as a function of the Higgs boson mass (M_h). The solid line corresponds to the previous world average for the top mass of 174.3 ± 5.1 GeV/c^2, with the blue band indicating the impact of theoretical uncertainty. The dashed line corresponds to the new DØ average for the top mass of 179.0 ± 5.1 GeV/c^2. The yellow shaded area on the left indicates the region of masses excluded by experiment ($M_h > 114.4$ GeV/c^2 at the 95% confidence level [3]). The improved top mass measurement puts the most likely value of the Higgs mass above the experimentally excluded range.
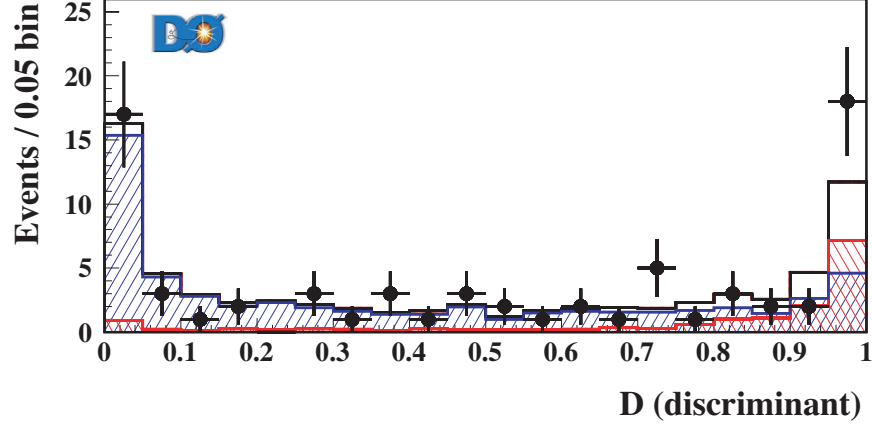
Figure 3: Distribution in the discriminant D (see text) calculated for the 71 $t\bar{t}$ candidates (data points), assuming the top mass of 175 GeV/c^2. The data are compared with results expected for the sum (open histogram) of the $t\bar{t}$ signal (red, left-hatched) and W+jets events (blue, right-hatched), simulated with MC. The data show an excess above W+jets background at large values of the discriminant, characteristic of the $t\bar{t}$ signal.
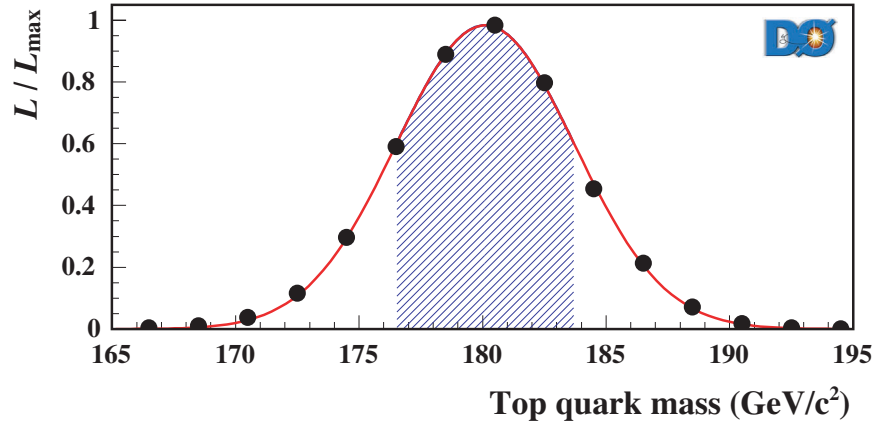

Figure 4: The points represent the likelihood of the fit used to extract the top mass, divided by its maximum value, as a function of the mass of the top quark (after a correction for the -0.5 GeV/c^2 mass bias, see text). The solid line shows a Gaussian fit to the likelihood. The maximum likelihood corresponds to the mass of 180.1 GeV/c^2, which is the new measurement of the top mass. The hatched band corresponds to the range of ± 1 standard deviation and indicates the ± 3.6 GeV/c^2 statistical error of the fit.

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